# An Attractor for Natural Supersymmetry

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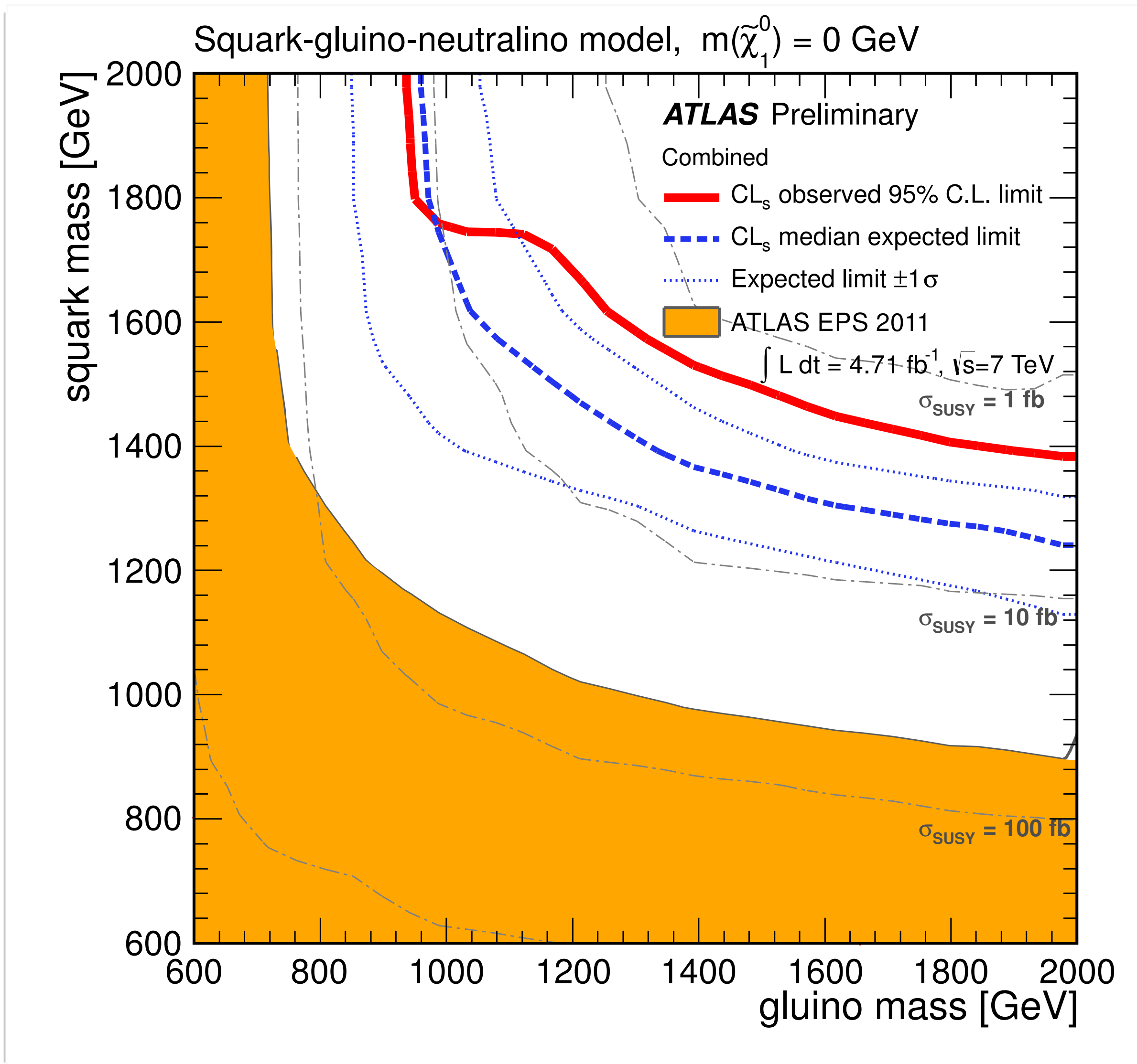
(SLAC)

with Anson Hook and Gonzalo Torroba

arXiv:1204.1337

Santa Fe "LHC Now" Summer Workshop
July 13, 2012

# The Status of Weak Scale SUSY




ATLAS-CONF-2012-033

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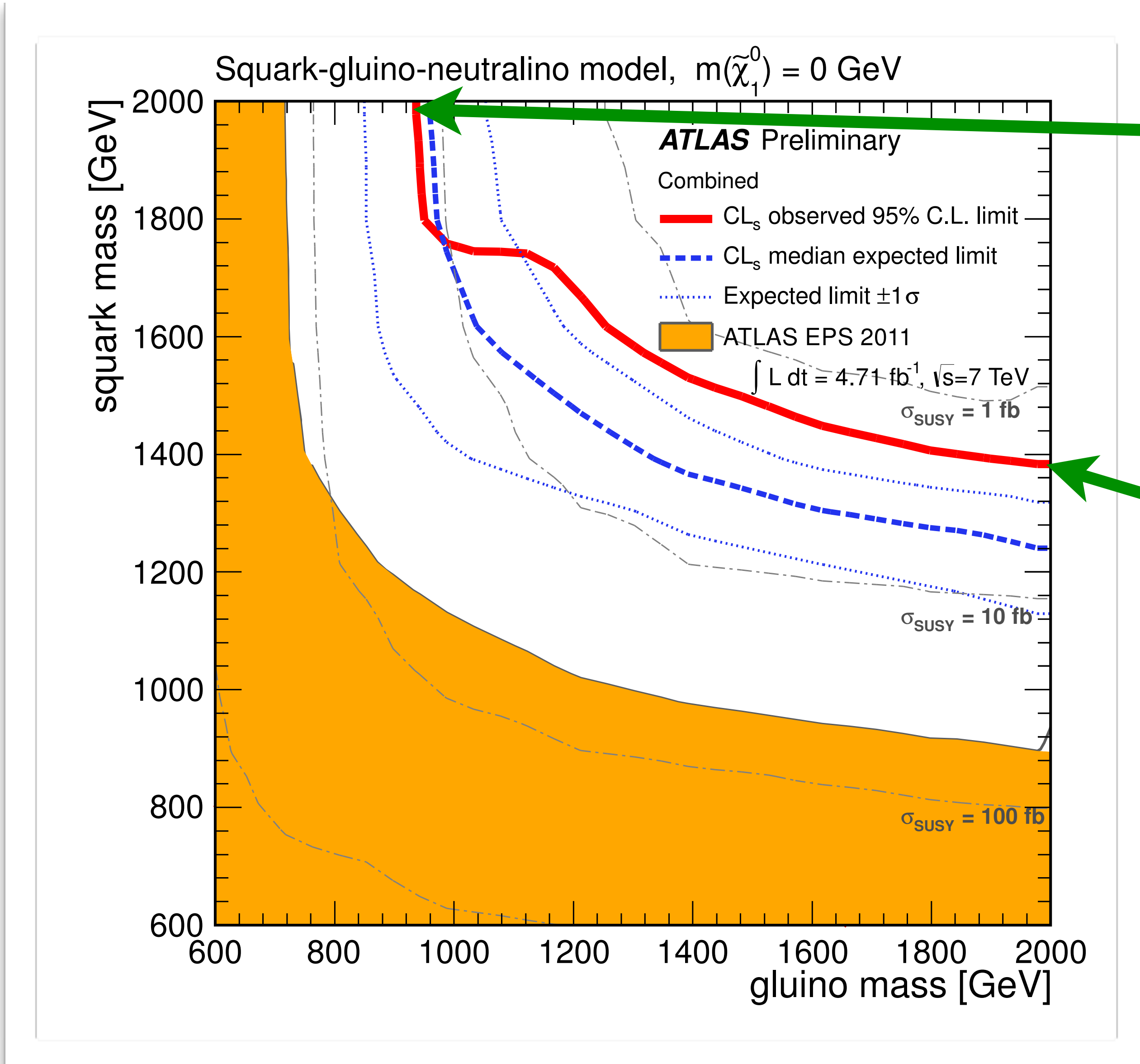


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$m_{\tilde{q}} \gtrsim 1.5$ TeV

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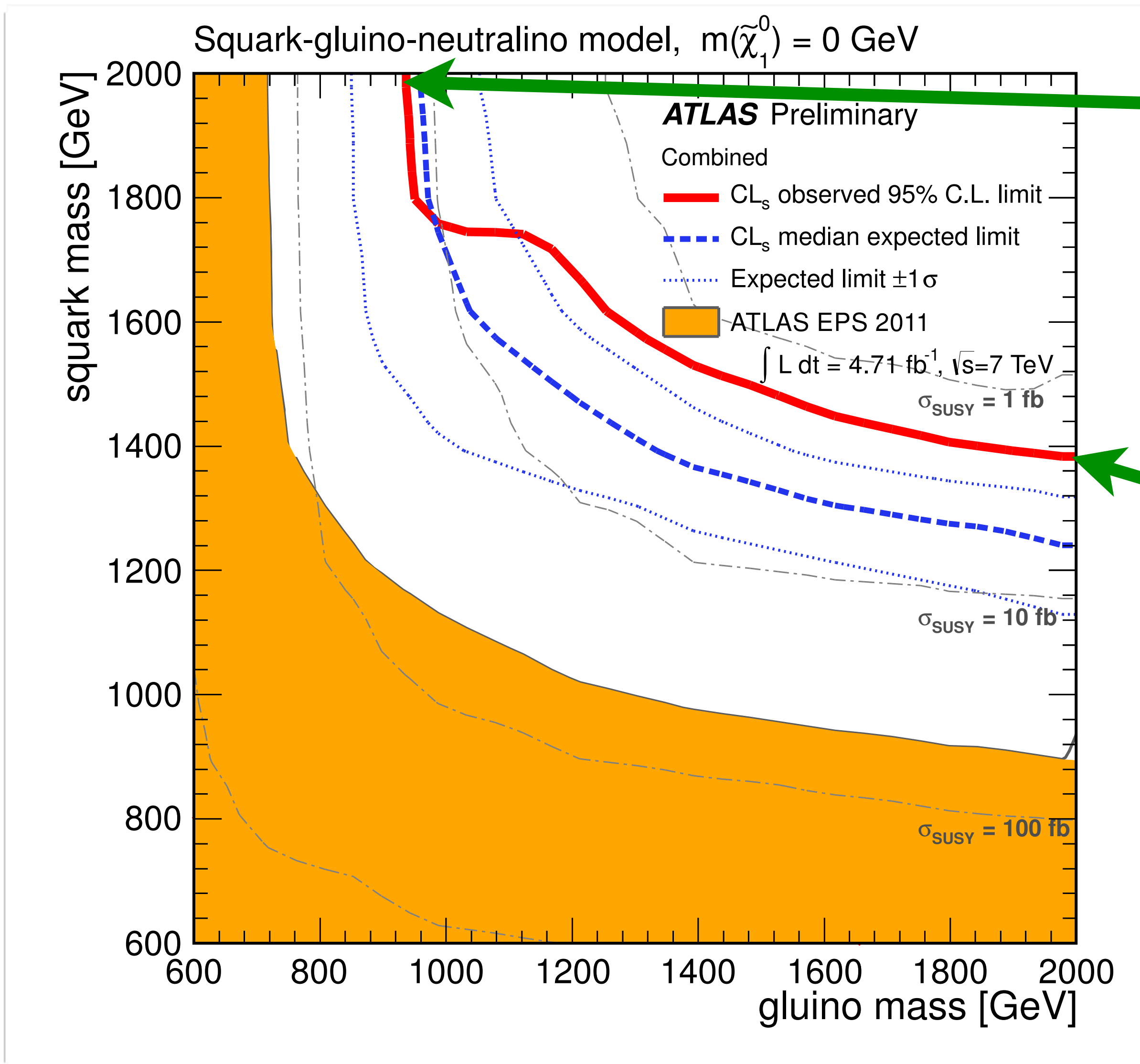


$m_{\tilde{g}} \gtrsim 1$ TeV

$m_{\tilde{q}} \gtrsim 1.5$ TeV

Does this tell us that the MSSM is unnatural?!?

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# “Natural Supersymmetry”

- Fine tuning in the MSSM:

$$-m_Z^2 \simeq 2\left(|\mu|^2 + \widetilde{m}_{H_u}^2\right)$$

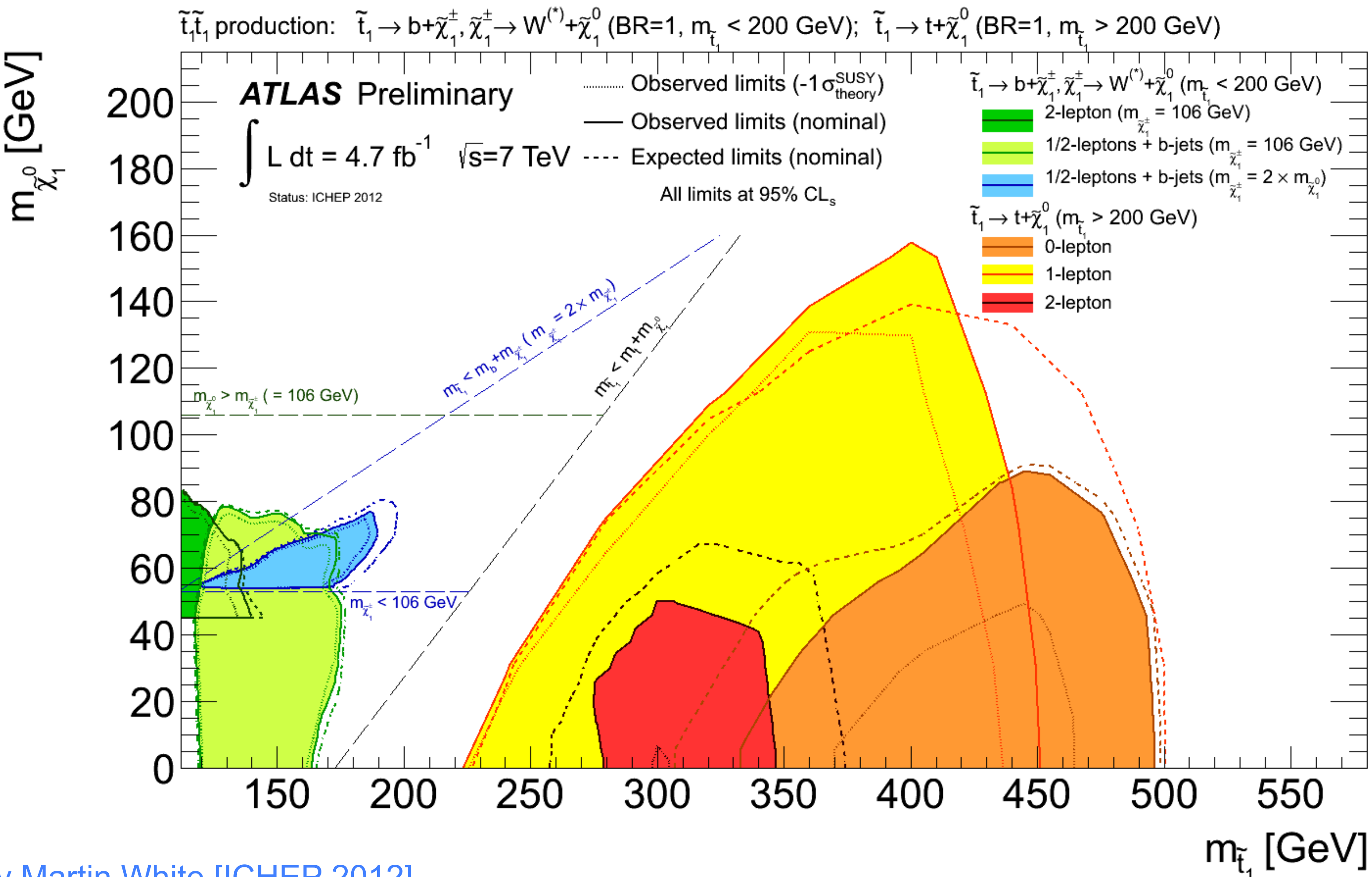
- Dominant contributions:

$$\delta\widetilde{m}_{H_u}^2 \simeq -\frac{y_t^2}{16\pi^2}\left(12\,\widetilde{m}_t^2\,\log\Lambda + \frac{32}{\pi}\alpha_s|M_3|^2\log^2\Lambda\right) + \ldots$$

# "Natural Supersymmetry"

- A "natural" spectrum only requires that the 3rd generation squarks and gauginos are light. Dimopoulos, Giudice [1995]; Cohen, Kaplan Nelson [1996]
  - Also referred to as a "split-family" or "more-minimal SUSY" spectrum.
- LHC bounds on these particles are weaker then on the 1st and 2nd generation squarks. Papucci, Ruderman, Weiler [arXiv:1110:6926]
- Helps alleviate flavor problems.
  - These models can not solve the flavor problem due to tachyonic constraints from 2-loop contributions.
- Known ways of mediating SUSY are flavor blind (e.g. gauge mediation)
- A "natural" spectrum requires novel model building.

# When is "Natural SUSY" dead?




Talk by Martin White [ICHEP 2012]

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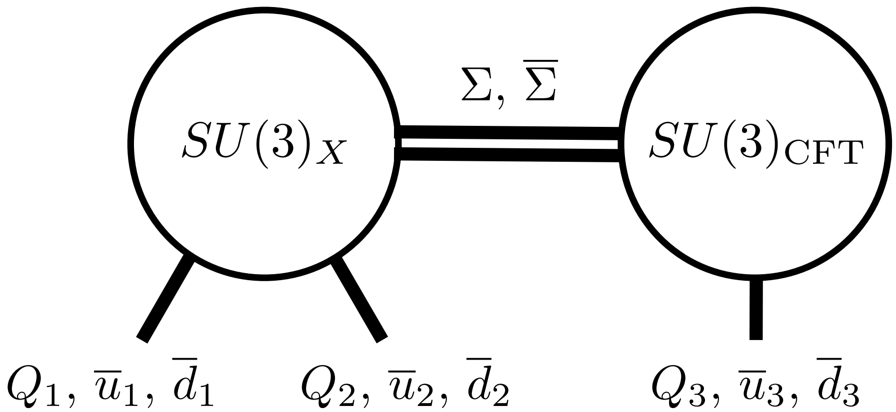
The Natural(er) MSSM

- Both stop soft masses and *A*-term are below O(TeV). The stop parameters do ***not*** imply a Higgs mass of 125 GeV.

# THE MODEL

# The Model

A quiver description:



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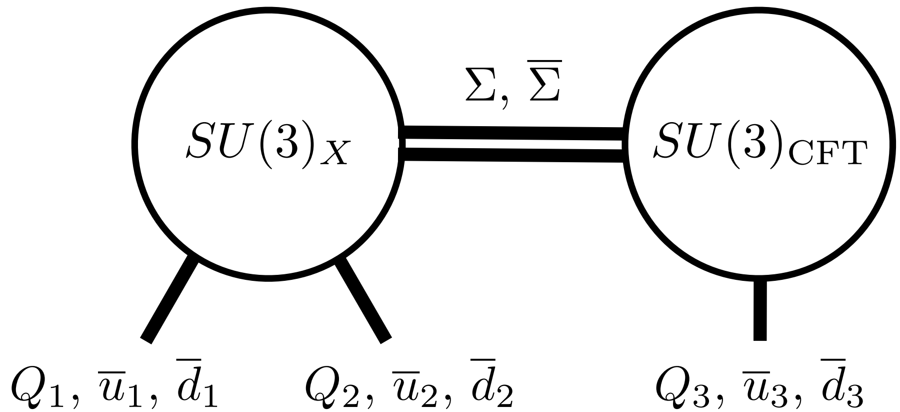


Relevant mass scales:

| | |
|---|---|
| $M$ | (the messenger scale) |
| $\Lambda_{\rm CFT}$ | (cross-over to the conformal regime) |
| $v$ | (exit the conformal regime) |
| $m_W$ | (the weak scale) |

The matter content:

| | $SU(3)_{\text{CFT}}$ | $SU(3)_X$ | $SU(2)_W$ | $U(1)_Y$ |
|---|---|---|---|---|
| $Q_3$ | $\square$ | $1$ | $\square$ | $1/6$ |
| $\overline{d}_3$ | $\overline{\square}$ | $1$ | $1$ | $1/3$ |
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| $H_u$ | $1$ | $1$ | $\square$ | $1/2$ |
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| $\Sigma$ | $\square$ | $\overline{\square}$ | $1$ | $0$ |
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| $A$ | $1$ | $1 + \text{adj}$ | $1$ | $0$ |
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Marginal superpotential:

$$W \supset Q_3\, H_u\, \overline{u}_3 + Q_3\, H_d\, \overline{d}_3 + \Sigma\, A\, \overline{\Sigma} + W_{\cancel{U(1)}}$$

Relevant deformation:

$$W \supset -v^2\, \mathrm{Tr}\, A$$

This relevant deformation forces $\langle \Sigma \overline{\Sigma} \rangle = v^2$ which breaks $SU(3)_{\mathrm{CFT}} \times SU(3)_X \to SU(3)_C$.

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O(1) Top Yukawa

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# CFTs and Soft masses

Nelson, Strassler [hep-ph/0104051]

- At the conformal fixed point, all physical couplings flow to their fixed point values.
- Promote couplings to superfields:
  - The higher theta components have mass dimension and thus flow to zero.
  - Since soft parameters are encoded as higher theta components of these superfields, certain combinations of soft parameters will flow to zero.

# CFTs and Soft masses

Nelson, Strassler [hep-ph/0104051]

- For generic superpotential couplings:

$$W \supset \lambda \prod_i \Phi_i^{n_i} \quad \Longrightarrow \quad \sum_i n_i\, \widetilde{m}_i^2 \to 0$$

- Promoting the gauge coupling to a superfield implies:

$$(\widetilde{m}_\lambda)_{\mathrm{CFT}} \to 0 \qquad \text{and} \qquad \sum \mathrm{dim}(r)\, T_r\, \widetilde{m}_r^2 \to 0$$

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- Since conserved currents are not renormalized, $\sum \mathrm{dim}(i)\, q_i\, \widetilde{m}_i^2$ does *not* flow to zero.
  - $q_i$ is the charge under a non-anomalous global $U(1)$ symmetry.

# Soft Masses

- Specify $W_{\cancel{U(1)}} = (Q_3\,\overline{u}_3)(Q_3\,\overline{d}_3)$.
- The remaining unbroken global $U(1)$ symmetries are given by:

| | $U(1)_1$ | $U(1)_2$ | $U(1)_3$ | $U(1)_R$ |
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| $Q_3$ | $1$ | $0$ | $0$ | $1/2$ |
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- This implies that the following combinations of soft masses are unchanged by the CFT dynamics:

$$\widetilde{m}^2_{\Sigma} - \widetilde{m}^2_{\overline{\Sigma}}$$

$$2\,\widetilde{m}^2_{Q_3} - \widetilde{m}^2_{\overline{u}_3} - \widetilde{m}^2_{\overline{d}_3}$$

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Note the *R* charges, which can be computed simply from considering the superpotential and the mixed anomalies.

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Nelson, Strassler [hep-ph/0006251, hep-ph/0104051]

# Yukawa Hierarchies

- Assume all Yukawa couplings are O(1) in the UV:

$$W \supset Y^u_{ij}\, Q_i\, H_u\, \overline{u}_j + Y^d_{ij}\, Q_i\, H_d\, \overline{d}_j + Y^u_{33}\, Q_3\, H_u\, \overline{u}_3 + Y^d_{33}\, Q_3\, H_d\, \overline{d}_3$$

- Recall that for a SCFT the anomalous dimension of fields is related to the *R* charge: $\gamma = 3R - 2$ .
- Then we can compute the RG evolution of the Yukawa couplings:

$$Y^u_{ij}(E) = \left(\frac{E}{\Lambda_{\mathrm{CFT}}}\right)^{\frac{\gamma_{Q_i}+\gamma_{u_j}+\gamma_{H_u}}{2}} Y^u_{ij}(\Lambda_{\mathrm{CFT}})$$

- Below the exit scale, the Yukawa coupling is given by

$$Y_{ij}(v) = \epsilon^{\frac{\gamma_H}{2}}\, Y_{ij}(\Lambda_{\mathrm{CFT}}) \ll Y_{33}(v)$$

with $\epsilon \equiv \dfrac{v}{\Lambda_{\mathrm{CFT}}}$ .

# Yukawa Hierarchies

- Since the 3rd generation and 1st/2nd generation fields are charged under different gauge groups, there is no way to write down a renormalizable off-diagonal Yukawa coupling.
- However, the following higher dimensional operators are allowed by the symmetries:

$$W \supset \frac{1}{\Lambda_*}\overline{\Sigma}\, Q_3\, H_u\, \overline{u}_{1,2} + \frac{1}{\Lambda_*} Q_{1,2}\, H_u\, \Sigma\, \overline{u}_3 + \ldots$$

- Below the exit scale these couplings flow to

$$Y^u_{i3}(v) = \frac{v}{\Lambda_*}\epsilon^{\frac{\gamma_{H_u}+\gamma_{Q_3}+\gamma_{\overline{\Sigma}}}{2}} \, , \; Y^u_{3i}(v) = \frac{v}{\Lambda_*}\epsilon^{\frac{\gamma_{H_u}+\gamma_{u_3}+\gamma_{\Sigma}}{2}}$$

with $\epsilon \equiv \dfrac{v}{\Lambda_{\rm CFT}}$ .

# Flavor

- The resultant IR Yukawa matrix is given by

$$Y^u \sim \begin{pmatrix} \epsilon^{\frac{\gamma_{H_u}}{2}} & \epsilon^{\frac{\gamma_{H_u}}{2}} & \xi_Q\, \epsilon^{\frac{\gamma_{H_u}}{2}} \\ \epsilon^{\frac{\gamma_{H_u}}{2}} & \epsilon^{\frac{\gamma_{H_u}}{2}} & \xi_Q\, \epsilon^{\frac{\gamma_{H_u}}{2}} \\ \xi_u\, \epsilon^{\frac{\gamma_{H_u}}{2}} & \xi_u\, \epsilon^{\frac{\gamma_{H_u}}{2}} & 1 \end{pmatrix}$$

with $\xi_Q \equiv \dfrac{v}{\Lambda_*}\, \epsilon^{\frac{\gamma_\Sigma + \gamma_{Q_3}}{2}}$ , $\xi_u \equiv \dfrac{v}{\Lambda_*}\, \epsilon^{\frac{\gamma_\Sigma + \gamma_{\bar{u}_3}}{2}}$ and $\epsilon \equiv \dfrac{v}{\Lambda_{\rm CFT}}$ .

- This structure can reproduce the mass hierarchy and CKM matrix to a good approximation by varying the O(1) starting value for the Yukawa couplings in the UV and taking

$$\frac{v}{\Lambda_{\rm CFT}} \sim 10^{-4}\,, \quad \frac{\Lambda_*}{\Lambda_{\rm CFT}} \sim 10^{-1} - 10^{-2}$$

# EXAMPLE SPECTRA

# Example Spectra

- At the exit scale $v$, the soft masses for the 3rd generation squarks and the Higgs scalars are zero (up to a small correction proportional to the gluino mass).
- The soft masses for the gauginos and 1st/2nd generations are unchanged by the CFT dynamics.

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- The soft masses for the gauginos and 1st/2nd generations are unchanged by the CFT dynamics.
- Choose a value of $M_3$ (assuming gaugino mass unification).
  - We then RG evolve the masses from the exit scale to the weak scale including the dominant 2-loop contributions.
  - The stop masses are generated via gaugino mediation.

    Kaplan, Kribs, Schmaltz [arXiv:hep-ph/9911293];
    Chacko, Luty, Nelson, Ponton [arXiv:hep-ph/9911323]
  - This drives the up-type Higgs soft mass negative resulting in electroweak symmetry breaking.

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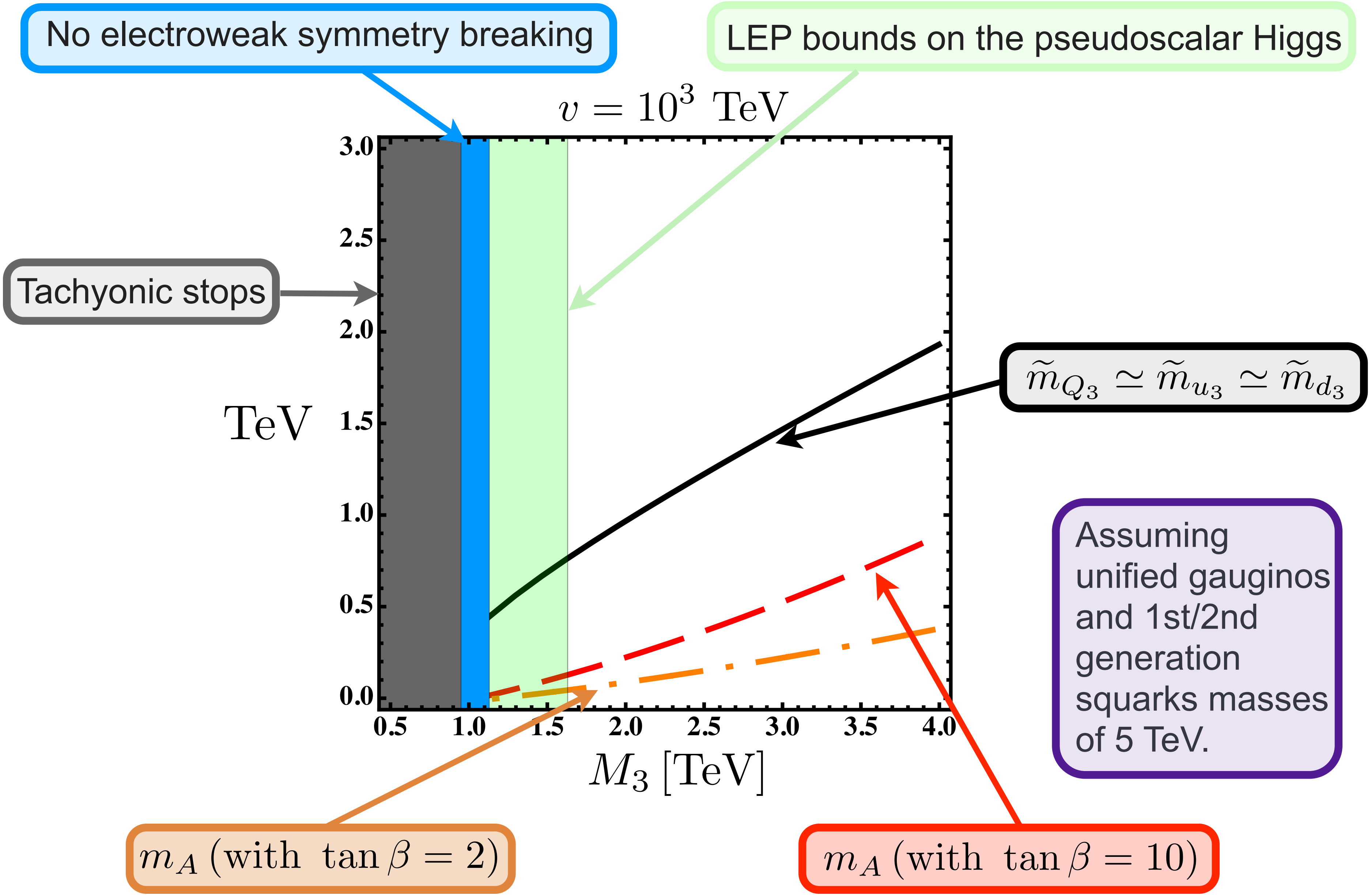
  - This drives the up-type Higgs soft mass negative resulting in electroweak symmetry breaking.
- Choose a value of $\tan\beta$.
  - The weak scale value of $\mu$ is determined from $-m_Z^2 \simeq 2\left(|\mu|^2 + \widetilde{m}_{H_u}^2\right)$.
  - This fixes the weak scale value of $b_\mu$ using the electroweak symmetry breaking conditions (at tree level).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LEP bounds on the pseudoscalar Higgs
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Tachyonic stops
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$M_3$ [TeV]
$\widetilde{m}_{Q_3} \simeq \widetilde{m}_{u_3} \simeq \widetilde{m}_{d_3}$
Assuming unified gauginos and 1st/2nd generation squarks masses of 5 TeV.
$m_A$ (with $\tan\beta = 2$)
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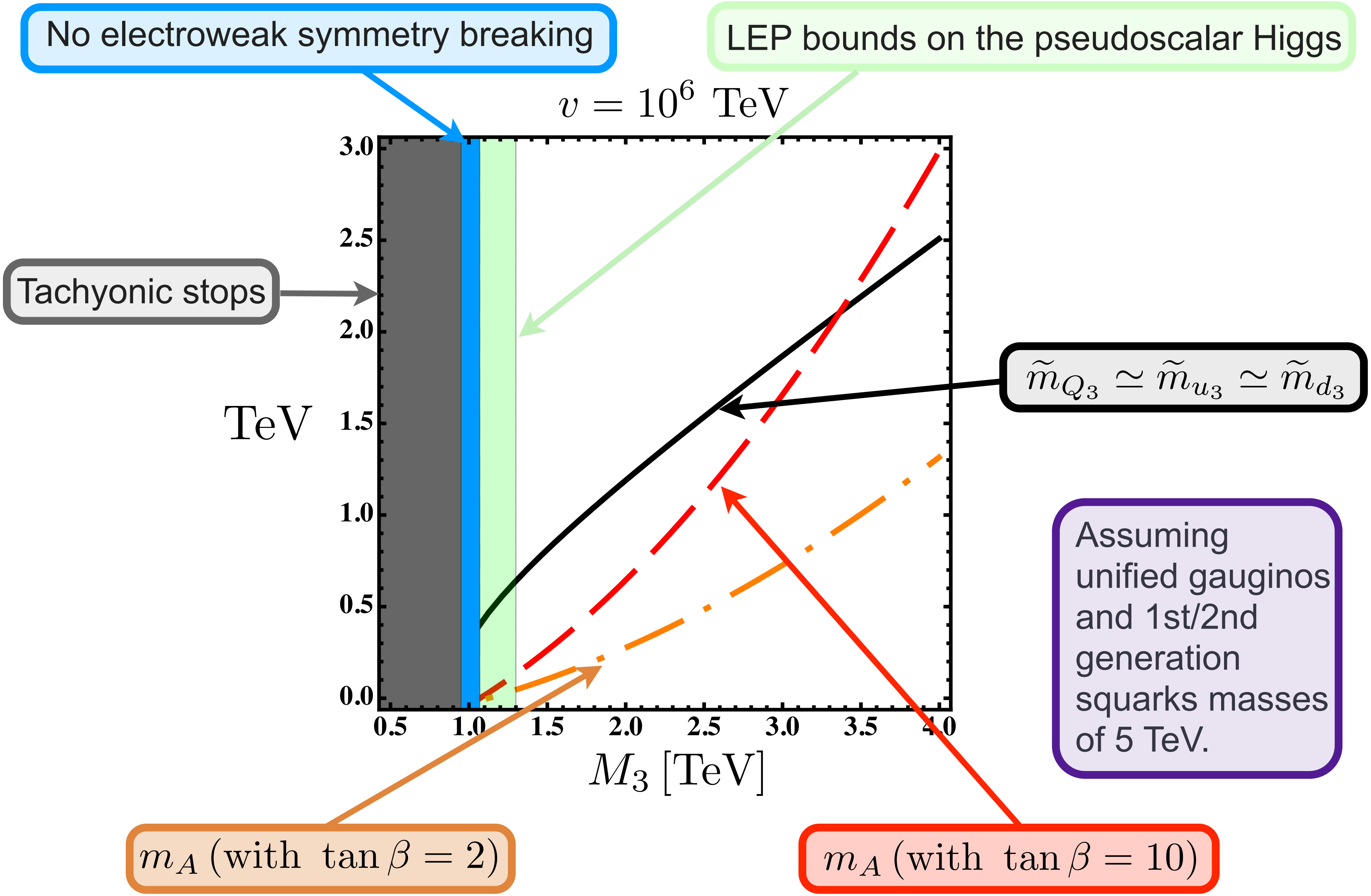

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# The Higgs Mass

- Our model does not explain a 125 GeV Higgs boson mass.
- Since the superpotential term $S H_u H_d$ is irrelevant while the CFT is strongly coupled, our model is incompatible with the NMSSM.
- To increase the Higgs mass, one can add a sector which results in non decoupling *D*-terms.

Batra, Delgado, Kaplan, Tait [arXiv:hep-ph/0309149]
Maloney, Pierce, Wacker [arXiv:hep-ph/049127]

- The results is to take all MSSM Higgs sector relationships and make the substitution:

$$m_Z^2 = \frac{g_Z^2}{2}\left(\langle {H_u}^2\rangle + \langle {H_d}^2\rangle\right) \quad \longrightarrow \quad \Xi^2 \equiv \frac{g_Z^2 + g_{\text{new}}^2}{2}\left(\langle {H_u}^2\rangle + \langle {H_d}^2\rangle\right).$$

  - In the spectrum plots we have assumed there is an additional *D*-term contribution to the Higgs quartic $\Xi = 150\ \text{GeV}$.

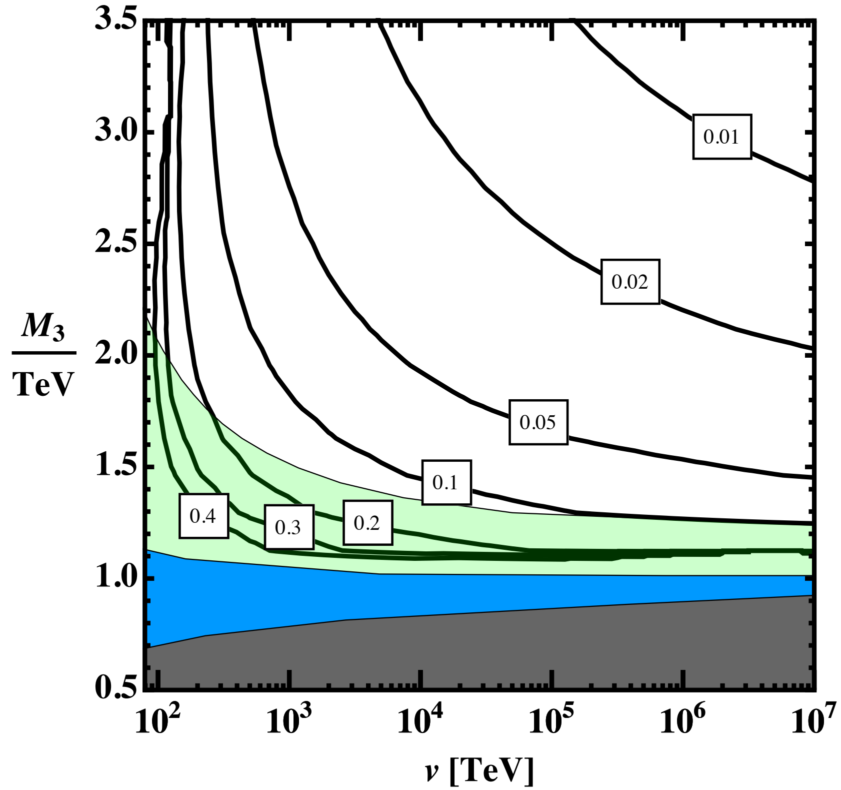
# CONCLUSIONS

# Conclusions

- Given LHC bounds on superpartners and the discovery of a Higgs at 125 GeV, we are being pushed to rethink the relationship between SUSY and naturalness.
  - Maybe SUSY is hidden
    - Compressed spectra
    - *R*-parity violation
    - Decays to hidden sectors
    - Something else?
  - Maybe there is a large hierarchy between the 3rd and 1st/2nd generations
- We have presented a model whose dynamics result in:
  - A split-family superpartner spectrum;
  - The hierarchical flavor structure of the quark Yukawa matrices.
- A given gluino mass implies the 3rd generation squark and Higgs sector masses.
- Currently, the strongest bounds on the spectrum are due to the non-observation of pseudo-scalar Higgs.

# BACKUP SLIDES

# Fine-tuning




Exclusion contours are as in the spectrum plots.

- To get a sense of fine-tuning in this model we adopt a naive low-scale measure. Kitano, Nomura [arXiv:hep-ph/0509039]; Papucci, Ruderman, Weiler [arXiv:1110:6926]
- Plotted are contours of $\Delta^{-1} \equiv -2\frac{\delta m_H^2}{m_h^2} = -2\frac{\widetilde{m}_{H_u}^2}{m_h^2}$, with $\tan\beta = 2$.
- We see large regions with O(10%) fine-tuning are allowed.